Design optimisation of swellable elastomeric seals using advanced material modelling and FEM simulations

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Stampede™ Swellable Packers

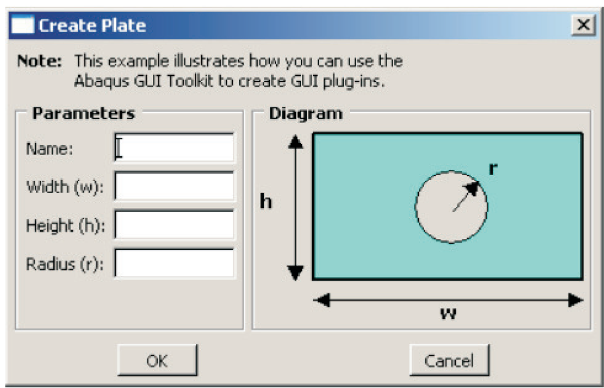
Design Features and Benefits:

- Proprietary elastomer compound provides predictable swell when in contact with well fluids and with changes in temperature.
- Robust end ring design, with multiple set screws, protects the rubber during run-in, and provides a barrier against extrusion.
- Elastomer is vulcanized to the base pipe, allowing the packer to have one effective annular seal.

Introduction & Objectives

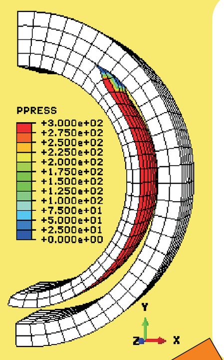
Swellable elastomeric seal is a type of specifically engineered packer that swell upon contact with wellbore fluids. Such packers have been widely employed in various oil-&-gas and minerals applications including slimming of well design, zonal isolation, water shut-off, and multi-stage fracturing. Downhole conditions are difficult to be reproduced using physical testing environment, but feasible to be simulated in virtual environment using CAE software. A better understanding of packers' mechanical behaviour in downhole conditions would provide a higher confidence and improvement of existing engineering design practices for manufacturing of packers. The numerical simulation can be incorporated into optimisation procedure searching for an optimal shape of packers with the goals to minimise the time to seal the borehole and maximise the contact pressure between the seal and borehole. Such an optimisation would facilitate the development of a packer with various designs optimised for different downhole conditions. The objective of this research project is to develop a design tool integrated into a CAE to implement parametric numerical studies using FEM simulation. However, development of such a CAE plugin is associated with a number of technical challenges specific to this class of multiphysics problems.

ABAQUS plugin with GUI



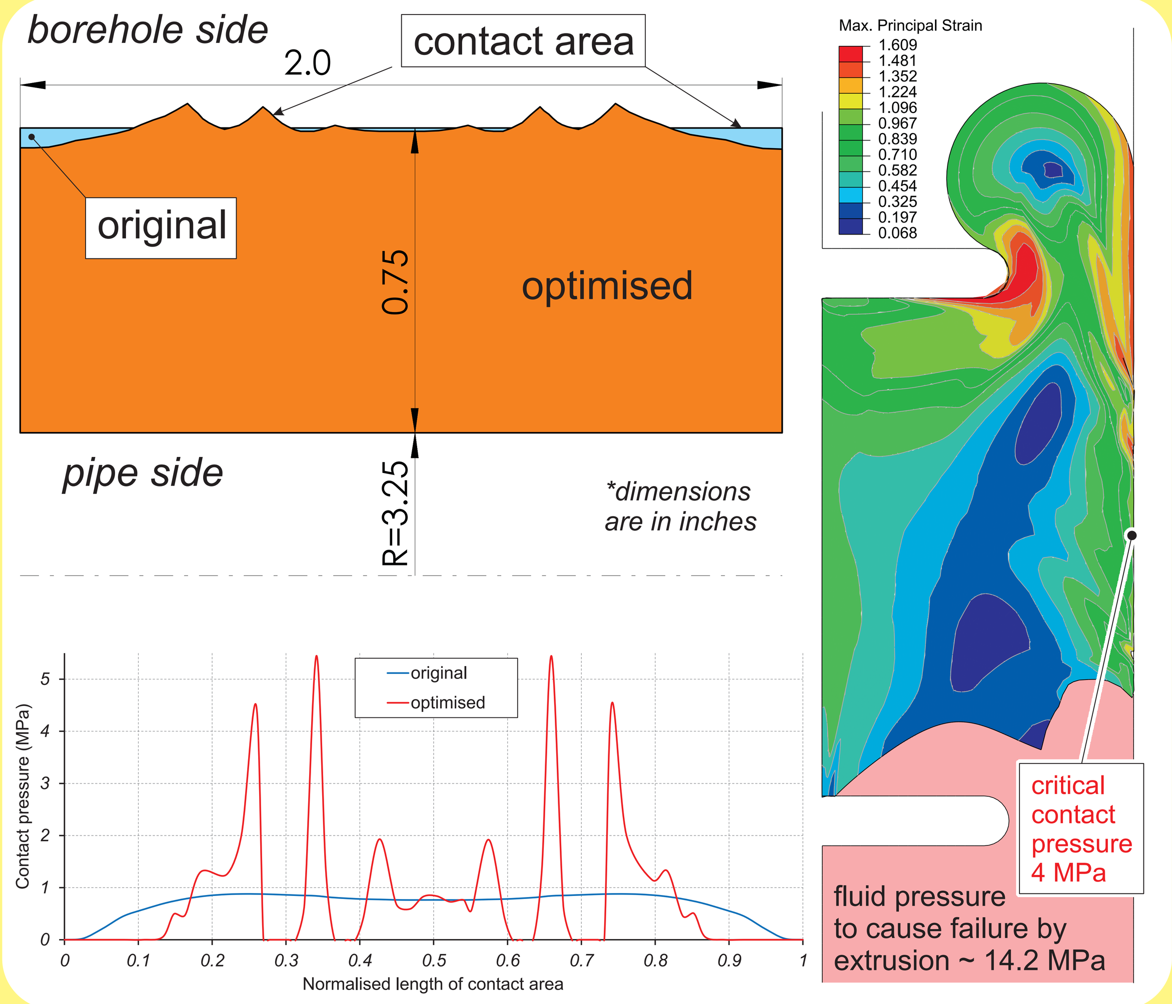
Parametric study assumes going through a big number of different geometric configurations, looking at material properties variation and different downhole conditions. This means a search for an optimal geometry through a sensitivity study, which would result into specific design recommendations for the geometry of a packer. It is reasonable to automate the analysis procedure through a Plugin with a convenient GUI, which provides access to the parameters of geometry, material, service conditions, etc.

Fluid pressure penetration



The moisture swelling process is not uniform and develops from the surfaces which are subject to fluid. Adsorption, which governs the progress of swelling can occur only at open surfaces. Therefore, the fluid pressure penetration technique needs to be involved into simulation. This is an automated application of fluid pressure dependent on changes of contact conditions.

Shape optimisation with Tosca Structure

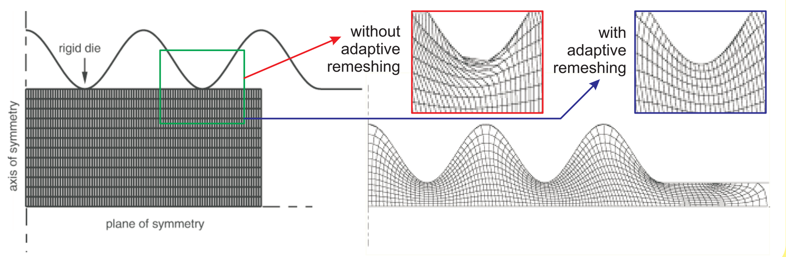


Robust Simulation of Swellable Packers

1 2 3 4

Adaptive remeshing

Non-uniform swelling can be associated with a localised increase of material volume. So it may cause a significant distortion of FE mesh and result into analysis convergence problems. To overcome this, an adaptive mesh-to-mesh solution mapping (rezoning) may be required.



Hyperelasticity with swelling

The key component is an advanced material model comprising both hyperelasticity and moisture swelling. It has to consider two-way interaction between mechanical properties and swelling capacity. Implementation of such material model requires programming of a Fortran subroutine for the user defined material using the Flory-Rehner theoretical background [2].

In polymer science Flory–Rehner equation is an equation that describes the mixing of polymer and liquid molecules as predicted by the equilibrium swelling theory of Flory and Rehner. It describes the equilibrium swelling of a lightly crosslinked polymer in terms of crosslink density and the quality of the solvent. The theory considers forces arising from three sources [2]:

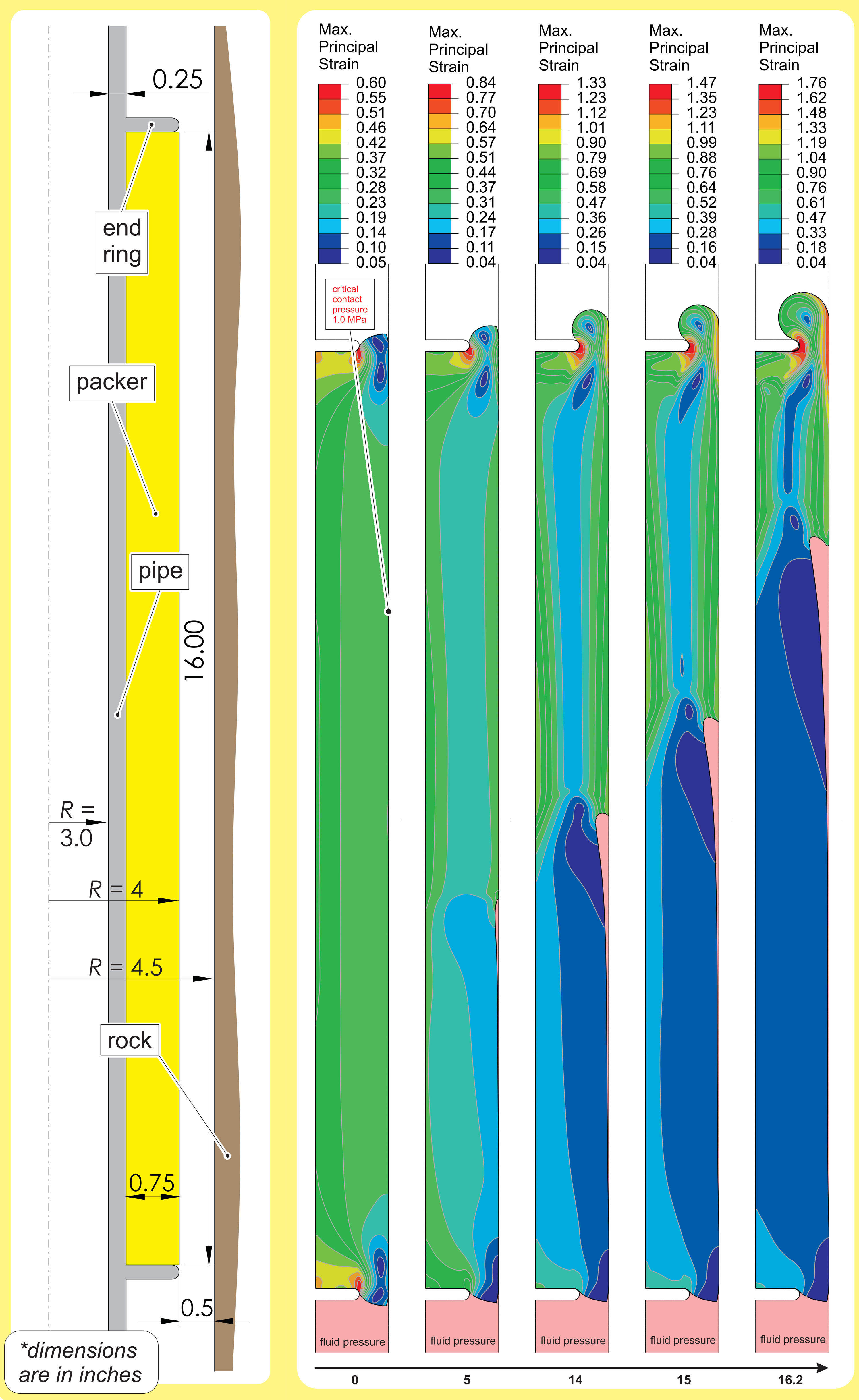
- The entropy change caused by mixing of polymer and solvent.
- The entropy change caused by reduction in numbers of possible chain conformations via swelling.
- The heat of mixing of polymer and solvent, which may be positive, negative, or zero.

The equation is written as

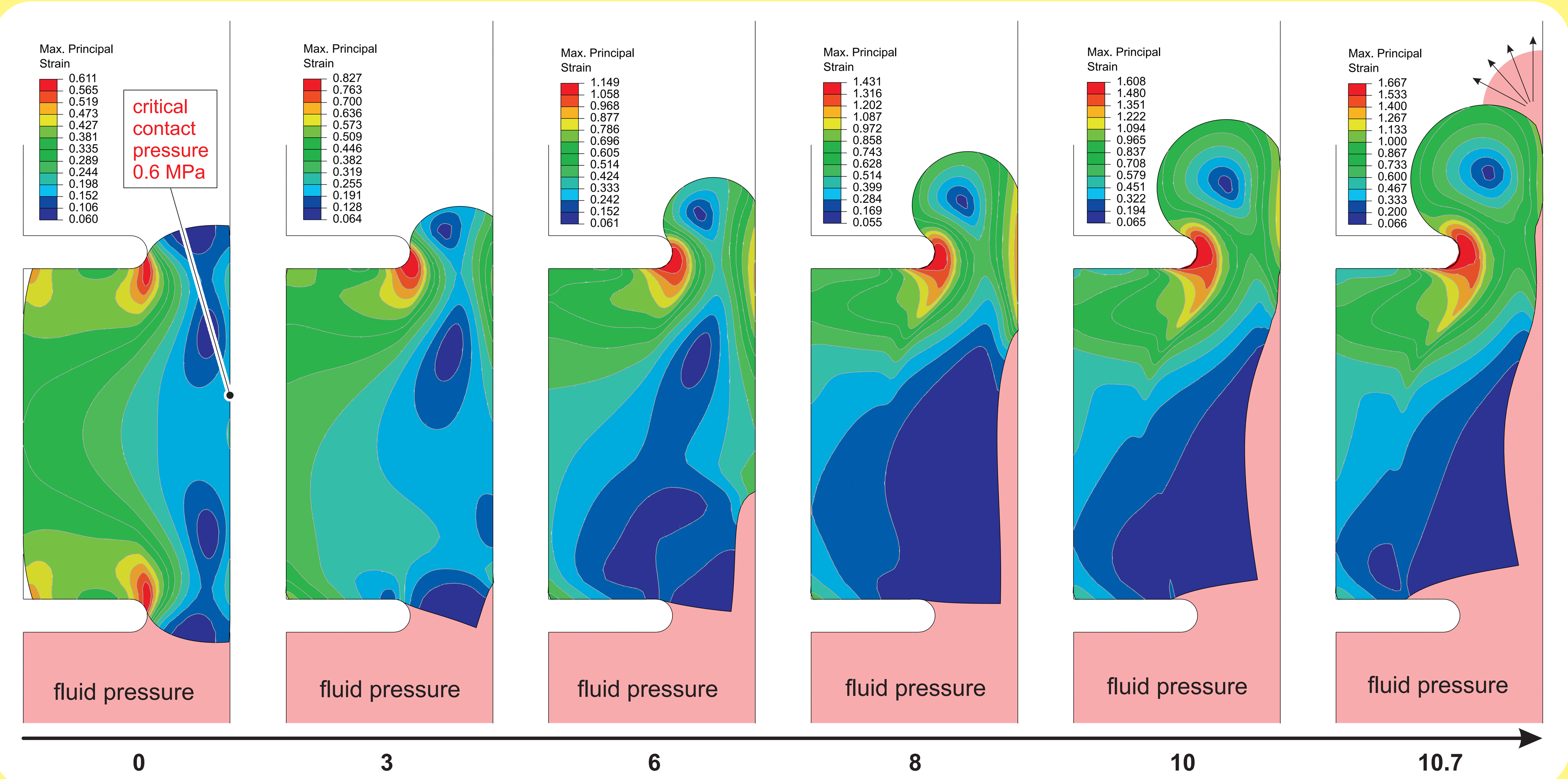
$$-\left[\ln\left(1-\nu_2\right)+\nu_2+\chi_1\nu_2^2\right]=V_1 n\left(\nu_2^{\frac{1}{3}}-\frac{\nu_2}{2}\right)$$

where ν_2 is the volume fraction of polymer in the swollen mass, V_1 the molar volume of the solvent, n is the number of network chain segments bounded on both ends by crosslinks, and χ_1 is the Flory solvent-polymer interaction term.

FE-simulation of Pressure penetration & leakage in packer



Benchmark problem for leakage and extrusion

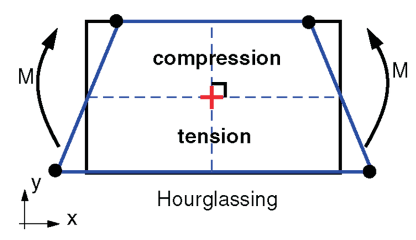


Discussion

1. Critical mechanical contact pressure for fluid pressure penetration:
To account for the asperities on the contacting surfaces, a critical contact pressure, below which fluid penetration starts to occur, is introduced. The higher this value, the easier the fluid penetrates. The default value of the critical contact pressure is zero, in which case fluid penetration occurs only if contact is lost.

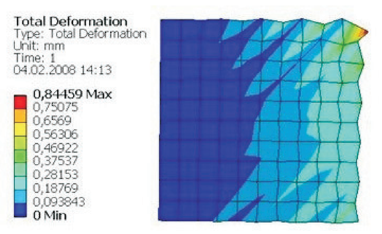
How much is it dependent on following?

- pressure and type of fluid,
- surface quality and material type of borehole,
- type of packer elastomeric material.



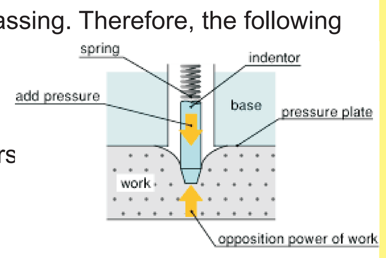
2. Amount of stiffness in hourglass control:

Hourglassing is essentially a spurious deformation mode of a FE-mesh, resulting from the excitation of zero-energy degrees of freedom. It typically manifests as a patchwork of zig-zag or hourglass like element shapes, where individual elements are severely deformed, while the overall mesh section is undeformed. This happens on hexahedral 3D solid reduced integration elements and on the respective tetrahedral 3D shell elements and 2D solid elements.



Assigning stiffness to the finite elements is used to suppress hourglassing. Therefore, the following questions arise:

- Can we relate this artificial stiffness to the "surface layer effect"?
- How much stiffness is right to be assigned to the elements?
- How do we measure the stiffness of the surface layer in elasmoters
- Which mechanical tests are needed? Indentation tests?



fluid pressure

how related?

element stiffness ⟷ critical contact pressure

Planned Research Outcomes

- Design and manufacturing of tools for mechanical testing of swellable elastomeric specimens and mechanical behaviour of packers in conditions resembling downhole operation.
- Mechanical characterisation of swellable elastomers used by Weir Oil & Gas USA for packers through experimental studies in Advanced Materials Research Laboratory (AMRL) in the University of Strathclyde (https://www.strath.ac.uk/amrl/)
- Implementation of an advanced material model of hyperelasticity with moisture swelling in FE-code and identification of corresponding material constants for it.
- Linking of moisture swelling with the fluid pressure penetration feature in order to simulate realistic non-uniform material expansion, which is more intensive on the areas that are in contact with fluids.
- Development of an optimisation procedures for available FEA packages (ABAQUS, ANSYS, MSC.Marc etc.) based on packers downhole behaviour simulation using an advanced material model.
- Implementation of parametric optimisation - to find an optimal length of a packer, and non-parametric (shape and topology) optimisation - to find an optimal packer profile. For this purpose Isight (parametric) and Tosca Structure (non-parametric) optimisation engines will be used.
- Optimised packers geometry is obtained by running the optimisation studies on the regional supercomputer centre at the University of Strathclyde – ARCHIE-WeSt (https://www.archie-west.ac.uk).
- Provision of packers design recommendations and optimal designs based on a number of optimisation studies for variety of downhole conditions in form of tables and/or mathematical relations.
- Delivery of the ABAQUS plugin to Weir industrial partners as a conventional tool for simulation-based design analysis and improvement.

References

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